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Control parameterization for power oscillation damping via software-in-the-loop simulation

Ha Thi Nguyen, Guangya Yang, Arne Hejde Nielsen, Peter Højgaard Jensen, and Carlos F.M. Coimbra

Abstract—The parameter optimization of designed controllers for power systems is always a big concern and needs a lot of effort of researchers especially when the electricity grid becomes larger and more complex. The paper proposes a control parameterization using genetic algorithms (GA) for power oscillation damping (POD) incorporating synchronous condensers via software-in-the-loop simulation to enhance the damping and frequency stability for low inertia systems. A closed-loop interfaced setup among real-time digital simulator (RTDS), Matlab, and OLE for Process Communication (OPC) running in real time is analyzed and implemented to optimize the POD parameters of a synchronous condenser. Furthermore, a Prony technique based on the system measurement is applied to find out the frequency and damping ratio of the dominant oscillation mode. The POD optimal parameters are determined by the GA objective function that maximizes the damping ratio of the dominant oscillation mode. The effectiveness of the proposed method in damping power oscillations and frequency stability improvement is verified through simulation results of the future Western Danish power system. Simulation results demonstrate that the proposed approach offers a good performance for parameter optimization of the POD.

Index Terms—Frequency stability, genetic algorithms, parameter optimization, power oscillation damping, software-in-the-loop simulation.

I. INTRODUCTION

The rapid increase of converter-based generation in the grid makes system dynamic characteristics significantly changing. Instability issues resulted from low-frequency oscillations because of low inertia operating conditions and weak interconnections among power systems are therefore more significant. This requires innovative solutions for an optimization of power system elements and controllers to guarantee the secure operation.

Traditionally, many supplementary controllers are implemented in power systems to address the oscillatory stability issues. Power system stabilizers (PSSs) implementation to existing power plants are used as an auxiliary excitation control to damp oscillations for power system stability enhancement. Besides, power oscillation damping (POD) using FACTS devices that control the angle of injection buses to adjust the power transferring on transmission lines [1], [2]. Coordinating existing PSSs with supplementary control of other components such as wind power plants [3], [4] or FACTS devices [5], [6], [7] are examined as well. However, how to optimize the control parameters is always a concern for control engineers. Several researchers have implemented optimization algorithms for determining optimal parameter set of controllers. In [8], a genetic algorithms (GA) optimization is applied for tuning

control parameters of the proportional-integral controller subject to the H_∞ constraints in terms of linear matrix inequalities of the state-space system model of three-area power system. Reference [9] proposes tuning strategy for robust pulse width modulated series compensator damping controller based on an augmented Lagrangian particle swarm optimization which satisfies the multiple H_∞ performance criteria for FACTS controller. A PSS parameter optimization using a trajectory sensitivity approach is examined in [10] for a multi-machine power system. A gradient-based nonlinear parameter optimization of FACTS devices via Real-Time Digital Simulator (RTDS) is investigated in [11], however, there is a limit for the optimization algorithm implementation in RTDS.

With the dominance of renewable generators in the modern power systems, new stability issues and requirements for the controls are introduced for the renewable-based systems. To have a smooth transition to the renewable energy system, a POD control design adapting to the modern system characteristics is extremely necessary. Synchronous condenser (SC) is proposed as a potential solution for low inertia systems to support inertia and short-circuit power [12], [13], [14].

To address these issues, the paper presents a software-in-the-loop simulation for parameter optimization of POD incorporating in SCs which uses a nonlinear optimization tool to enhance the power oscillation and frequency stability of low inertia systems.

The rest of the paper is organized as follows. The software-in-the-loop simulation for parameter optimization of POD which is a closed-loop and runs in real time with RTDS, OLE for Process Communication (OPC), and Matlab communications is introduced in Section II. Section III presents the methodology using for parameter optimization for POD. A test result based on the future Western Danish power system is investigated in section IV to verify the benefit of SiL simulation of the POD parameter optimization. Some important conclusions are finally drawn in section V.

II. SOFTWARE-IN-THE-LOOP SETUP

The perspective future Western Danish power system run in RTDS platform is driven by a MatLab script for system startup and disturbance simulations. The data of the system is collected by OPC server and sent directly to Matlab workspace. In MatLab, the signal is processed first to remove the fundamental frequency component from the response signal. The oscillation component is analyzed by Prony analysis for determining the frequency and damping ratio of the dominant oscillation mode. The damping ratio

is maximized by GA objective function to find the better parameters of POD and update the RTDS model for further verification. These steps are iterative by a closed-loop and run in real time with RTDS, OPC and Matlab communications as shown in Figs. 1 and 2. The loop will continue until the objective function satisfying the damping ratio maximization of the dominant mode constraint to determine the optimal values of POD parameters.

In order to communicate with Matlab, RTDS has to run the ListenOnPort command and becomes a Transmission Control Protocol (TCP) server. This server listens to a designed port and waits for an incoming connection request from Matlab script. Once the connection is established, RTDS runtime becomes a socket server and Matlab is a socket client. RTDS runtime is controlled by a Matlab script via the TCP communication. To collect the data from OPC, a communication setup is established between MatrikonOPC and Matlab through OPC toolbox that allows to access to live and historical OPC data directly from Matlab/Simulink.

A. RTDS setup

The whole DK1 system is modeled and compiled in RSCAD/Draft. To run the system by a Matlab script, a communication connection is established between RSCAD/Runtime and Matlab. Once the connection is implemented, RTDS runtime becomes a socket server and Matlab is a socket client. RSCAD/Runtime is commanded and run in real-time by a Matlab script via the TCP server [15]. In addition, the new parameter set of POD controller is updated via this communication as well.

RTDS exchanges data to external equipment over a LAN/WAN using the Distributed Network Protocol (DNP). To send the measurement data to OPC, a GTNET card equipped with the DNP firmware is installed in one of the RTDS racks where the measured signal must be located in. A points mapping text file with a .txt suffix is used to map DNP data points to input/output signal names assigned in RSCAD/Draft.

B. OPC setup

In order to collect the data from RTDS, a communication channel between RTDS with MatrikonOPC is setup with 3 steps including RTDS network channel, RTDS network host, and RTDS DNP3 which is described detail in [16]. After the communication is established, RTDS and OPC can exchange the data to each other. The measurement data is collected in OPC server and sent to Matlab for next steps.

C. Matlab program

A Matlab script commands and runs the system in real-time at RSCAD/Runtime through TCP communication. To acquire the data at OPC server, a connection is setup in a Matlab script to create a group object with specific defined properties. After getting the data and then through a signal processing to convert to proper format, it is retrieved in Matlab workplace for further analysis. When the data is sent to Matlab, OPC cleans up and disconnects to prepare for next data collections. A polynomial

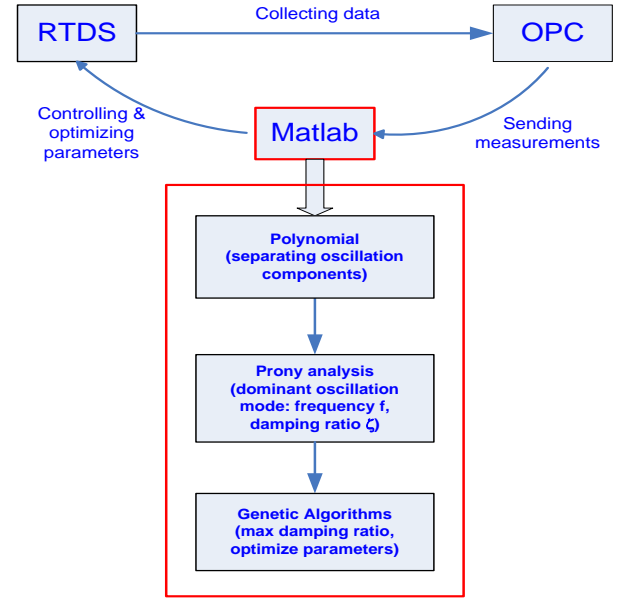


Fig. 1. System arrangement of SiL simulation.

function is implemented to remove the fundamental frequency component from the response signal. After that, Prony technique is applied to extract the frequency and damping ratio of the dominant oscillation mode. Based on the damping ratio, the better parameter set of POD controller is found out based on GA objective to achieve the damping ratio maximization of the dominant oscillation mode.

The parameter set is sent to RSCAD/Runtime by a Matlab command for next iteration. These steps are repeated continuously until one of the termination parameters is achieved. The GA may be terminated after a certain number of generations when the objective value does not enhance after a certain generation. As a result, a near-optimal or optimal solution for POD parameter set is determined. The entire procedure is illustrated in Fig. 2.

III. METHODOLOGY

A. Prony analysis

Prony analysis is a least-square approximation technique of fitting a linear sum of exponential terms to a measured signal. A brief overview of this technique is given in [17]. The important feature of this technique is directly determining the frequency, damping ratio, energy, and relative phase of modal components present in a given measurement signal by an extending Fourier analysis [18]. The ability to extract such information from transient signal simulations would be overcome the computing burden of the linear model for large-scale systems.

Consider a generally continuous signal $y(n)$ that is to be modeled by

$$y(n) = \sum_{i=1}^p (b_i z_i^n) = \sum_{i=1}^p A_i e^{j\theta_i} e^{(\alpha_i + j2\pi f_i)n\Delta t} \quad (1)$$

with

$$\begin{cases} b_i = A_i e^{j\theta_i} \\ z_i = e^{(\alpha_i + j2\pi f_i)n\Delta t} \end{cases}$$

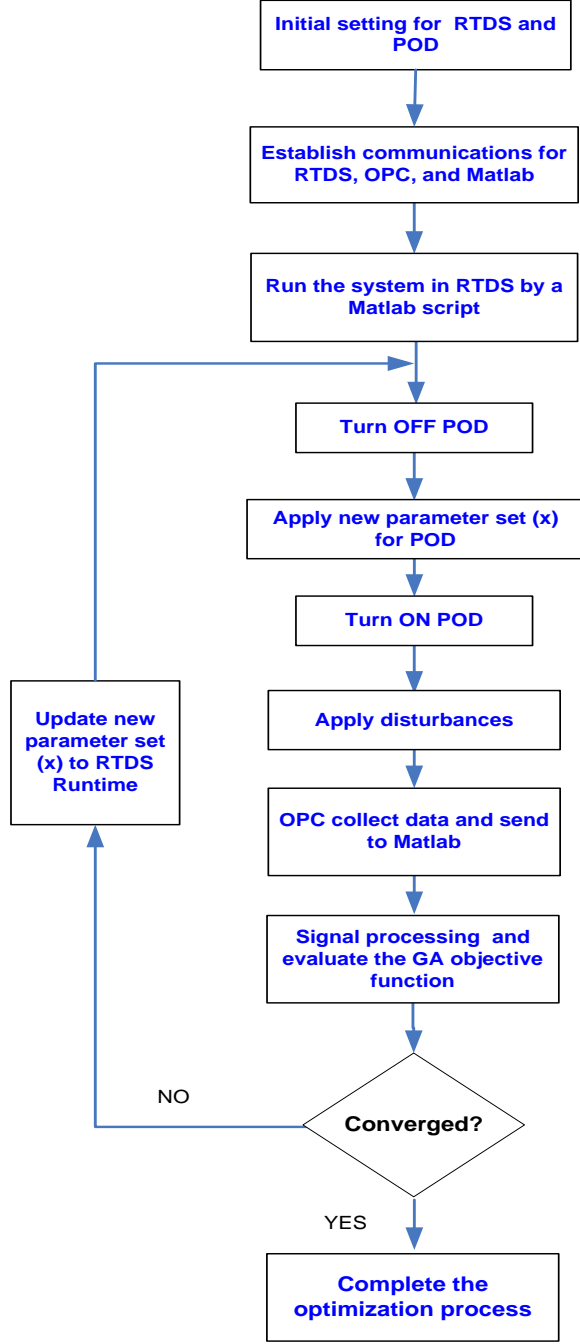


Fig. 2. The overall procedure of optimization process with SiL.

where $n = 0, 1, 2, \dots, N - 1$ with N is the sampling number, Δt represents the time interval of sampling, p is the order of Prony mode. A_i and θ_i are the amplitude and inception phase angle of the i th oscillation mode. f_i and α_i represent the frequency and damping ratio of the i th oscillation mode, respectively.

Overall, the Prony analysis can be summarized into three steps:

1. Constructing a linear prediction model from the measured data and solving it.

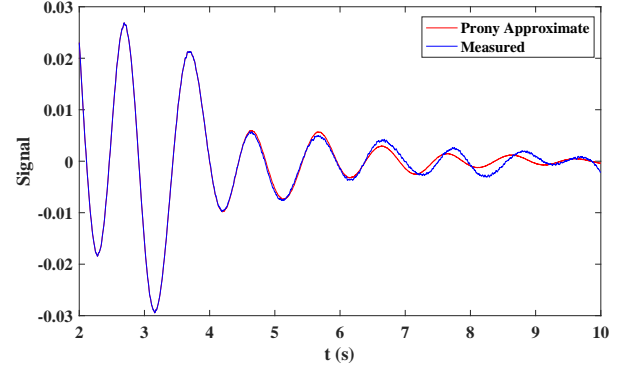


Fig. 3. The comparison of Prony analysis and the measurement signal.

2. Computing the discrete-time poles of the characteristic polynomial equation generated by the linear model which in turn results in the eigenvalues.

3. From these eigenvalues, the damping ratios and oscillation frequencies and related parameters could be extracted.

Before determining the information of the measured data, a signal processing step is implemented to remove the fundamental frequency. This step separates the oscillatory component for Prony analysis conduction. The Prony analysis obtains many oscillation modes which include dominant modes and disturbance modes. This results from the mixing noise and trend in the measurement which cannot be eliminated completely in the signal processing step.

The dominant mode is recognized by the energy analysis approach which evaluates the contribution of each oscillation mode, is expressed as follows:

$$E_i = \sum_{n=0}^{N-1} (R_i z_i^n)^2 \quad (2)$$

where E_i , R_i , and z_i are the energy, the amplitude, and the pole of the i th oscillation mode, respectively; $i = 1, 2, \dots, p$. The dominant mode is the biggest energy contribution to the oscillation.

A comparison of prony approximate and measurement is shown in Fig. 3 which presents how accurately the prony analysis works in this study.

B. Genetic algorithms

GA is a global heuristics parameter search technique based on genetic operators to find the optimal or near-optimal solutions for each specific problem [19], [20]. Unlike the traditional optimization approaches that require one starting point, GA uses a set of points (chromosomes) as the initial condition and each chromosome is evaluated for its performance according to the objective function which characterizes the problem to be solved and defined by the designers. A group of chromosomes is called a population. In this paper, five parameters of the POD controller are optimized by a damping ratio maximization objective function of GA. The process of GA is applied as follows:

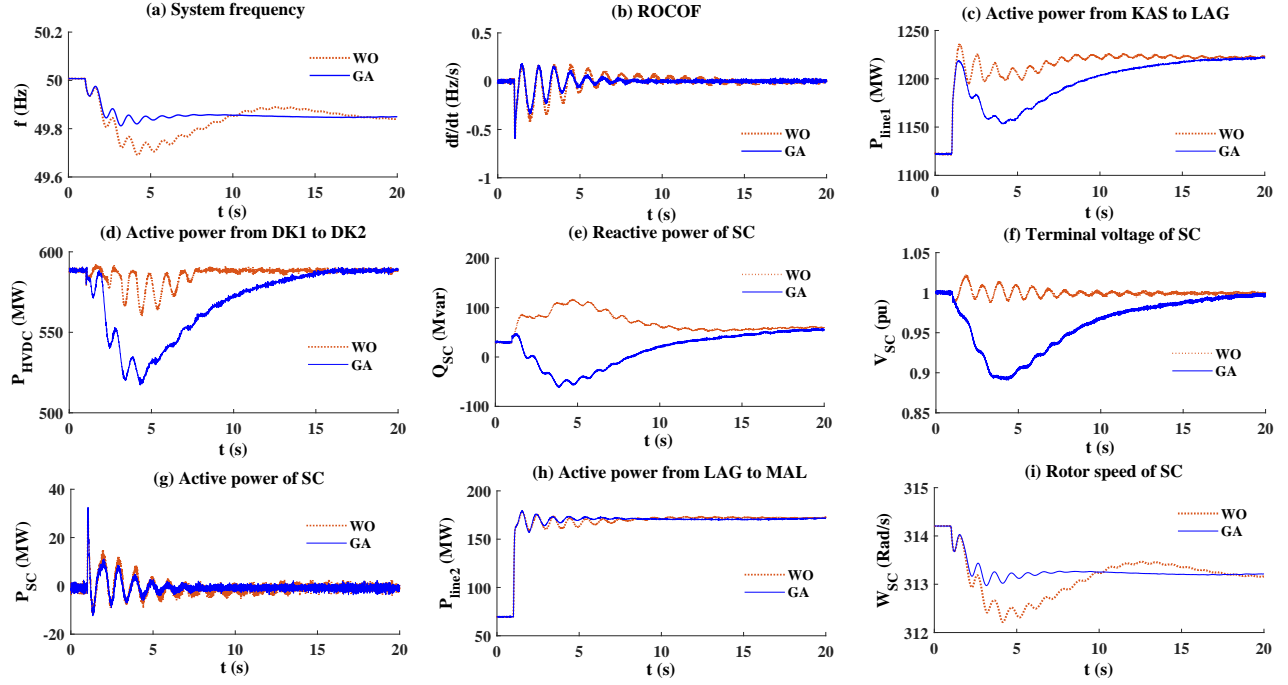


Fig. 4. Load increase scenario: (a) System frequency. (b) ROCOF. (c) Active power from KAS to LAG. (d) Active power from DK1 to DK2 through HVDC connection. (e) Reactive power of SC. (f) Terminal voltage of SC. (g) Active power of SC. (h) Active power from LAG to MAL. (i) Rotor speed of SC.

1. Initialization: a number of individuals which represent the POD parameters are randomly created according to the initial population, upper and lower bound setting.

2. Objective evaluation: Using a selection operator, the algorithms select the best result for each individual in accordance with their values defined by the objective function. The main goal of the control system is the damping ratio maximization of the system oscillation mode, i.e.,

$$f(x) = \max \left\{ \xi = -\frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} \right\} \quad (3)$$

where α and β are real and imaginary parts of the dominant mode, respectively. It means that GA finds out the variables x based on boundary settings to maximize the damping ratio ξ of the oscillation mode.

3. Reproduction: a new set of chromosomes are generated from the selected parameters in step 2 using selection, crossover, and mutation operators. These genetic operators ensure a larger average objective value for next generation.

4. Termination flagged: these 3 steps are repeated continuously until one of the termination parameters is achieved. The GA may be terminated after a certain number of generations when the objective value does not enhance after a certain generation.

IV. CASE STUDY

In order to verify the performance of SiL simulation of POD parameter optimization, a load increase scenario is investigated in this section.

Fig. 4 shows comparative results of system frequency, ROCOF, active power on transmission line KAS to LAG, HVDC link from DK1 to DK2, and SC responses WO in the dot red line and with GA-based POD in the solid blue one, respectively. From the comparative results, while uncontrolled system exhibits a severe oscillation and large frequency deviation, the system with POD controller performs a better damping and frequency deviation improvement. As seen that the system frequency in Fig. 4(a), without POD it experiences a large and long oscillation (the dominant mode with 0.596 % damping ratio) as well as a huge deviation (0.3 Hz) before getting a new equilibrium. On the contrary, with GA-based POD these parameters are significantly improved 14 % of damping ratio and 0.18 Hz of the frequency deviation, respectively. By comparing ROCOF, a faster damping and a quicker settling down are obviously seen in Fig. 4(b) with POD controller.

An opposite trend is observed from the reactive power response of SC during the disturbance without and with POD controller. Instead of rapidly increasing the reactive power from around 31 Mvar to approximately 114 Mvar to keep the voltage constant at the nominal value as WO case, POD decreases the terminal voltage by absorbing around 90 Mvar reactive power (from 31 Mvar to around -59 Mvar) to control the power flow. Consequently, a large decrease and less oscillation are observed from the active powers on the transmission lines and HVDC link with POD controller as shown in Fig. 4.

TABLE I
WITHOUT AND WITH GA COMPARISON OF DOMINANT MODE.

Cases	Domi. mode	Freq (Hz)	Dam. ratio	Fre. peak (Hz)
WO	-0.037+j6.217	0.992	0.00596	49.7
WGA	-0.998+j6.8452	1.09	0.145	49.82

As expected, the active power of SC rapidly supports kinetic energy and quickly settles down while the rotor speed is significantly improved both the deviation and the damping with POD controller as seen in Fig. 4(g) and (i). As a result, the power oscillation and frequency stability are significantly improved during the disturbance with POD controller. The parameters shown in Table I summarize the Prony analysis of the dominant mode with a significant enhancement of the system with POD controller.

V. CONCLUSION

To deal with the oscillatory stability issue for the modern power system where new stability issues and requirements for the controls are introduced, this paper proposes a SiL simulation for parameter optimization based on a nonlinear optimization tool of POD controller to enhance the stability issue of low inertia systems. Furthermore, a Prony technique is applied to extract the system oscillation characteristic from the data measurement which benefits for large-scale systems with thousands of variables. It can be seen clearly from the comparative results that SiL simulation can offer a good parameter set for POD to enhance the damping and frequency stability during the disturbances. In addition, parameter optimization algorithm can help control designers saving time while still offers a near-optimal or optimal solution for the control parameter set. This SiL simulation can be applied to any optimization tool by modifying the algorithm in Matlab command.

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